Geochemical Monitoring of the Bay of Fundy Salmon Mariculture Industry from 1998 to 2000

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May 2001

Canadian Technical Report of Fisheries and Aquatic Sciences 2361

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Canadian Technical Report of
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101-06033/

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This is the two hundred and forty-fourth Technical Report of
the Biological Station, St. Andrews, NB

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Cat. No. Fs 97-6/2361E ISSN 0706-6457

Correct citation for this publication:

Wildish, D. J., H. M. Akagi, and E. Garnier. 2001. Geochemical monitoring of the Bay of Fundy salmon mariculture industry from 1998 to 2000. Can. Tech. Rep. Fish. Aquat. Sci. 2361: iii + 19 p.

ABSTRACT

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During 1998-2000, decisions about organic enrichment effects at salmon farms within the Bay of Fundy were made during an annual environmental monitoring program (EMP) which is based on qualitative criteria. Presented here are quantitative geochemical results based on redox potentials and total sulfides in surface sediments, obtained by "shadow sampling" at the same locations and time that the qualitative EMP observations were made. Comparing the qualitative and proposed quantitative criteria for defining three (qualitative) or four (quantitative) grades of organic enrichment showed essential agreement, although with some differences. The comparison suggests that the quantitative method would give similar ratings with increased objectivity. Spring versus fall geochemical data comparisons were inconclusive because of the widespread use of fallowing at many sites during this study, which biased our results.

RÉSUMÉ

Wildish, D. J., H. M. Akagi, and E. Garnier. 2001. Geochemical monitoring of the Bay of Fundy salmon mariculture industry from 1998 to 2000. Can. Tech. Rep. Fish. Aquat. Sci. 2361: iii + 19 p.

De 1998 à 2000, on a pris des décisions concernant les effets de l'enrichissement organique dans les installations salmonicoles de la baie de Fundy, dans le cadre d'un programme annuel de suivi environnemental (PSE) fondé sur des critères qualitatifs. Le présent document expose les résultats de données géochimiques quantitatives (fondées sur les potentiels d'oxydoréduction et la teneur en sulfure des sédiments de surface), qui ont été obtenues par un échantillonnage « parallèle » aux mêmes endroits et dates où ont été faites les observations qualitatives du PSE. En comparant les critères qualitatifs et les critères quantitatifs proposés pour définir trois niveaux (qualitatifs) ou quatre niveaux (quantitatifs) d'enrichissement organique, on constate que les résultats sont essentiellement les mêmes, à quelques différences près. Cette comparaison laisse entendre que la méthode quantitative donnerait des résultats semblables, tout en assurant une plus grande objectivité. Les comparaisons des données géochimiques recueillies au printemps et à l'automne n'étaient pas concluantes, en raison du grand nombre de sites inactifs, qui ont entraîne une distorsion des résultats.

INTRODUCTION

Prior to 2000, the New Brunswick environmental monitoring program (EMP) of the salmon mariculture industry was based on qualitative methods carried out by a SCUBA diving team to examine sediments (Thonney and Garnier 1994; Washburn and Gillis 1995). In 1999, the Aquaculture Environment Coordination Committee (AECC) recommended that future annual sedimentary surveys include quantitative geochemical methods, in particular the measurement of redox and sulfide levels in surface sediments taken by SCUBA divers, directly under the sea cages. One clear advantage of this approach is that, by adopting the organic enrichment gradient concept of Poole et al. (1978) and Pearson and Rosenberg (1978), it is possible to convert the sediment geochemical data into four broad groups along the gradient (Table 1). Such groups have considerable practical utility in determining when to undertake remediation steps as explained by Janowicz and Ross (2001). Any site designated as a "C" will be required, under the new guidelines, to have additional sediment monitoring and take remediation management actions to reverse the trend to anoxia and local extinction of macrofauna.

The geochemical criteria limits for each group within the organic enrichment gradient were determined by Wildish et al. (2001) following consideration of a broad, local database (including Hargrave et al. 1995, 1997; Wildish et al. 1999, 2001), as well as some of the geochemical data presented here.

Before agreeing to change their recommendation regarding the method of environmental monitoring for the NB salmon mariculture industry, the AECC sought answers to the following questions:

- how do the 1998, 1999 and 2000 geochemical data, obtained in field sampling conditions, compare with earlier research results?
- how do the qualitative ratings of the old EMP (A, B, C only) compare with the new (A, B+, B-, C) ones?
- how do spring versus fall geochemical data compare?

This report attempts to answer these questions, as well as record the data on which it is based, for future comparative use.

MATERIALS AND METHODS

All field sampling was by SCUBA diving with the diver pushing a 4.5 x 50 cm core tube into the sediment, and following the protocol described in Wildish et al. (1999). The number of transects used at each site depended on the farm size, and three samples for sediment geochemistry were taken on each transect. Because of industry sensitivities, each farm is identified by an arbitrary number only, which remains consistent throughout each of the three sampled years.

The redox probe was placed in a hole drilled in the core tube after removing duct tape, which covered it, followed by withdrawing a 5-cc sample in a cut-off plastic syringe for sulfide determination. Redox, expressed as mV_{NHE}, and sulfide, expressed as µM, were determined as in Wildish et al. (1999), except that 4.0 M KCl was used to fill the redox probe and not 0.2 M KCl, as incorrectly stated in this report. In 1998, 5-cc sediment samples for sulfide were kept in plastic vials in an ice chest for transport to the laboratory, where they were fixed in sulfide anti-oxidant buffer solution. Orion ISE: silver/sulfide half cell (#9416) and reference electrodes (#90-01) were used to determine the sulfide concentration. In 1999 and 2000, both redox and sulfide determinations were completed in the field.

Redox probes (Orion, 96-78-00) in field use were frequently refilled with 4 M KCl filling solution (Orion, 900011), checked against Zobell's solutions A and B and found to be within the limits described in Wildish et al. (1999). The sulfide probes were calibrated, just before use on each sampling day, by checking against freshly prepared $Na_2S.9H_2O$ solutions at two concentrations (100 and 1000 µM), as in Wildish et al. (1999).

For each completed measure of redox plus sulfide concentration, we have used Table 1 criteria to assign the sample to one of four groups: A, B+, B- and C. We have adopted the following approach to this, desiring that both Eh and $S^=$ results indicate the organic enrichment index state, but if there is disagreement, the least enriched state is the one recorded.

RESULTS

The fall data on which this report is primarily based are shown in Appendix 1 for 1998, Appendix 2 for 1999 and Appendix 3 for 2000.

Table 1. Organic enrichment groups and their geolochemical criteria (based on Wildish et al. 1999, 2001).

	Group			
Criteria	Normal	Oxic	Hypoxic	Anoxic
Eh_{NHE}, mV	>+100	0-100	-100-0	<-100
$S^=$, µM	<300	300-1300	1300-6000	>6000
N.B., EMP	A	B+	B-	C

COMPARISON WITH RESEARCH RESULTS

The research data of Hargrave et al. (1995, 1997), obtained in 1994 throughout the Fundy Isles mariculture area, was compared with the 1998 monitoring data of Appendix 1. The results (Fig. 1) show that the fitted regression lines of both sets of data are similar in slope, but differ in position of the slope (intercept). Thus, the Eh values of 1994 are less than those for 1998. This is consistent with a slight difference in procedure used by Hargrave et al. (1995, 1997), where the redox ion selective electrode (ISE) was filled with 0.2 M KCl versus 4.0 M KCl in all monitoring results. The approximately 85 mV greater response with saturated KCl obtained when tested with Zobell's solutions provides a satisfactory explanation for the difference in intercept shown in Fig. 1. All of the redox data reported by Hargrave et al. (1995, 1997) were determined with diluted KCl, whereas that reported by Wildish et al.(2001), including the 1999 technical report, were determined with saturated KCl.

Fitted regression constants for the relationship:

$$y = a\,Ln(x) + b$$

where $y = Eh_{NHE}$ in millivolts and x = sulfide in µM for all monitoring data, are shown in Table 2. Statistically there is no difference in intercept for any of the pairs of data shown in Table 2, although the 1998 data is different from the other data (Fig. 2)in position of the slope. Possibly this is related to the widespread use of fallowing in 1998, which resulted in increases of redox values due to recovery after fallowing.

COMPARING QUALITATIVE AND QUANTITATIVE ORGANIC ENRICHMENT GRADIENT RATINGS

We employed two protocols to produce the ratings shown in Appendices 1-3, based on the quantitative, geochemical results. The protocols were:

1. Geo(1), each subsample, consisting of one Eh and sulfide determination, was rated individually to designate the organic enrichment group to which it belonged, and

2. Geo(2), median values of all Eh and sulfide determinations (three per transect) at all transects (the number being determined by the farm size).

If Eh and sulfide determinations indicated different groupings, the least enriched one was the one recorded in Appendices 1-3.

From the results shown in the Appendices, we found that 12 of 65 classifications in 1998, 11 of 32 in 1999 and 11 of 50 in 2000 were different between the qualitative and quantitative methods (Table 3). In the 2000 data (Appendix 3), station 19 is classified A by EMP and B- by the Geo(2) method.

Table 2. Fitted regression constants with standard errors (S.E.) for the relationship between Eh_{NHE}, mV and sulfide, as Ln µM, for each year.

Year	a ± S.E.	b ± S.E.	N	r^2	Equation
1998	-57.02 ± 2.76	+476.91 ± 20.54	367	0.54	(1)
1999	-68.66 ± 2.90	+516.15 ± 19.77	201	0.74	(2)
2000	-47.88 ± 1.93	+329.81 ± 13.67	336	0.65	(3)*

*17 zero values for sulfide removed from data.

Table 3. Organic enrichment gradient classification disagreements between qualitative (N.B., EMP) and proposed quantitative method (Geo (2)).

Protocol		Sampling station number/year		
N.B., EMP	Geo (2)	1998	1999	2000
B	A	57, 50, 10		
A	B+	11, 2, 1	43, 40, 19, 14, 29, 28, 27	26, 8, 9, 42, 39, 64
C	B-	49, 28, 20, 18, 15	56, 32, 15, 54	15, 46, 58, 61

COMPARISON OF SPRING/FALL "C" STATIONS

Four sites - 3, 56, 59 and 61 - were compared in April 1998 and August-November 1998 (see Table 4). All of these sites had previously been designated as "C" sites by the regular qualitative monitoring carried out in the fall of 1997. One factor that should be recalled in assessing the results of Table 4 is that all of the sites considered were fallowed in 1998 because of problems with infectious salmon anemia.

Because the range of values is limited at the few highly organically enriched sites available for this comparison, the R^2 values are low:

Spring data (Table 4):

$$y = -53.84 \ln(x) + 304.09, R^2=0.25, N=40 \quad (4)$$

Fall data (Table 4):

$$y = -55.61 \ln(x) + 443, R^2=0.39, N=30 \quad (5)$$

where $y = Eh_{NHE}$ in mV and $x = S^=$, µM. The slopes for each regression line are similar but the intercept for spring data is much lower than that of the earlier fall data. This difference is due to an ~125 mV difference between spring and later fall values. This is consistent with a marked improvement in redox conditions at these sites due to recovery after fallowing.

RELATION BETWEEN REDOX, SULFIDE AND VOLATILE SOLIDS CONTENT OF SEDIMENT

A relatively crude method of measuring organic carbon - burning a weighed sediment mass for a period of 30 or 60 min at high temperature (550°C), followed, after cooling, by re-weighing - was also used during the annual EMP monitoring. Intuitively, the amount of carbon present in surface sediments should be in direct relationship with the degree of organic enrichment expected at that site.

To validate this, we have regressed redox and sulfide values on the percentage volatile solids (x) determined for each sample in 1998. The results show that the Eh value (y) at a surface site is related semilogarithmically to percentage volatile solids by

$$y = -101.28 \ln(x) + 262.64, R^2=0.63 \quad (6)$$

whereas the same relationship, but with y = sulfide µM, is not closely related by the regression equation yielding the highest R^2 value:

$$y = 705.52^{0.0737x}, R^2=0.25 \quad (7)$$

Previously, we have measured organic carbon in some local estuarine sediments by two crude methods: as the percentage Walkley-Black carbon (x) for the Saint Croix (Wildish et al. 1978), Musquash (Wildish 1977) and Digdeguash (Wildish et al. 1980) estuaries, as well as percent volatile solids (y). After removal of one outlier from the Saint Croix estuary data (station 14), a power fit best describes the data:

$$y = 4.6297x^{0.5778}, N=61, R^2=0.87 \quad (8)$$

This relationship can be used to predict the equivalent percent volatile solids, where only Walkley-Black carbons have been measured.

DISCUSSION

We believe that the results presented here provide answers to the questions posed in the Introduction. Thus:

1. Does the previous research and monitoring data presented for 1998-2000 provide consistent and reliable indications of the sulfide and redox values?

   The differences in position of the regression lines for previous research and the 1998-2000 monitoring data are adequately explained by a slight difference in method. Thus, in the earlier

Table 4. Comparison of spring/fall 1998 redox and sulfide levels at four stations.

Date	Site	Eh, mV_{NHE}	Sulfide µM	Date	Eh mV_{NHE}	Sulfide µM
07/04/98	59	-172.5	1200	06/11/98	98	1100
		-157	1200		-26	3200
		-149	1200		3	2100
		-148	1300		-36	1700
		-143	1300		-56	1600
		-138	1300		-48	1500
		-130	1400			
		-126	1400			
		-126	1500			
		-36	1700			
15/04/98	56	-116	750	05/11/98	-74	19000
		-111	830		-120	16000
		-109	900		-113	20000
		-108	1200		-117	18000
		-96	1200		-122	8800
		-93	1200		-121	17000
		-86	1300			
		-81	1500			
		-44	1500			
		-11	1600			
16/04/98	3	-166	2900	26/08/98	138	1100
		-165	3000		172	2700
		-163	3200		163	1600
		-156	3300		-14.6	5900
		-153	4000		18	6500
		-148	4400		72.1	7700
		-147	4400		-105.6	3700
		-142	4800		-101	13000
		-138	5100		-92	6700
		-127	6100			
09/04/98	61	-27	700	30/11/98	-16	3600
		-21	800		18	1200
		-16	1000		-4	1100
		-8	1000		-56	3500
		-6	1100		-26	4900
		-6	1100		-47	3900
		-4	1100		-6	3200
		10	1100		14	3300
		18	1300		-12	3200
		24	1400			

research results of Hargrave et al. (1995, 1997), the redox filling solution used (0.2 M KCl) was more dilute than that used to obtain the monitoring results (4.0 M KCl). This explains the approximately 85 mV greater values for the monitoring data in redox values. Otherwise, sulfide and redox values are consistently and reliably related inversely as shown in Fig. 1. For reasons of consistency, we recommend that all future monitoring data be obtained by using a redox probe filled with 4.0 M KCl.

2. Do the qualitative ratings of the present EMP (Washburn and Gillis 1995) correspond with those based on quantitative redox and sulfide measurements (Wildish et al. 1999)?

Most of the disagreements shown in Table 3 involve changes to adjacent groups, hence B to A and, in the reverse direction, A to B+. Since these have less significance in environmental monitoring management, they are not considered further here. Instead, we concentrate our attention on the reasons why some sites designated as "C" by the qualitative NB EMP method classify as B- by the quantitative geochemical method (Table 3).

The differences of C to B- shown in Table 3 appear to be mainly caused by mixed results, such that redox values indicate B-, whereas sulfide levels suggest C. In some cases, the results between different transects are quite different (e.g. #20 in 1998, see Appendix 1), suggesting considerable heterogeneity of organic enrichment under and near the cage footprint. For #49 in 1998 (Appendix 1), only one transect was run and the three results along it are consistently B- for both redox and sulfide. For #54 in 1999, the recorded geochemical result of B- (Appendix 2) is due to the median value of Eh - 99 mV, sulfide = 8200 µM, yet three of six redox and all six of sulfide values indicate a C site. One other anomalous result, not shown in Table 3, is #3 in 1998 (Appendix 1), is classified as a C by the qualitative method and a B+ by the quantitative method. Perusal of the Appendix 1 data for this site shows that each of the three transects gave consistently different results, again emphasizing the spatial complexity involved.

The above considerations suggest two important points in conducting environmental monitoring at mariculture sites. The first is that the fieldwork must be done directly under the cages where the maximum impact is to be expected. The second is that the detailed protocol needs to be adjusted so that remediation initiation can be timely. Thus, if the quantitative rating criteria were changed so that when redox and sulfide measures indicated different groupings, the most enriched one was adopted. Using this approach, most of the B- values in Table 3 would become C's. One advantage of this protocol would be to emphasize sulfide over redox values. In our experience, sulfide is a more persistent and conservative measure in comparison to redox, which rapidly changes as organic enrichment inputs are changed, e.g. during site fallowing.

3. Are measurements consistent between seasons?

Redox and sulfide measurements made on a few 'C'-rated farm sites were compared in April and November 1998. The spring data showed consistently lower redox values (~125 mV), but this appears to be explained by fallowing of these sites, begun in 1998 and caused by the infectious salmon anemia (ISA) outbreak in the Bay of Fundy industry. We conclude that our data cannot be used to investigate whether seasonal changes of redox and sulfide levels can be expected in continuously operated farms.

We have also investigated whether crude methods of measuring organic carbon, such as measuring the volatile solid content, as have been used in the EMP, can indicate within the local area the degree of organic enrichment. For 1998 mariculture data, the Eh is related semi-logarithmically to percentage volatile solids with a coefficient of correlation of 0.63. However, previously published data for local estuaries, such as the Digdeguash with mean (± range) % V.S. = 8.81(4.86-11.30), show that natural levels in unpolluted systems may exceed the elevated levels caused by salmon mariculture. It is probable that the availability of carbon for oxidation in the Digdeguash estuary is very low, whereas that under fish farm sites is very high. This demonstrates the limitation of the total volatile solid measure to indicate carbon "availability" for biochemical oxidation as opposed to total carbon, and shows that it cannot be used universally to define organic enrichment conditions.

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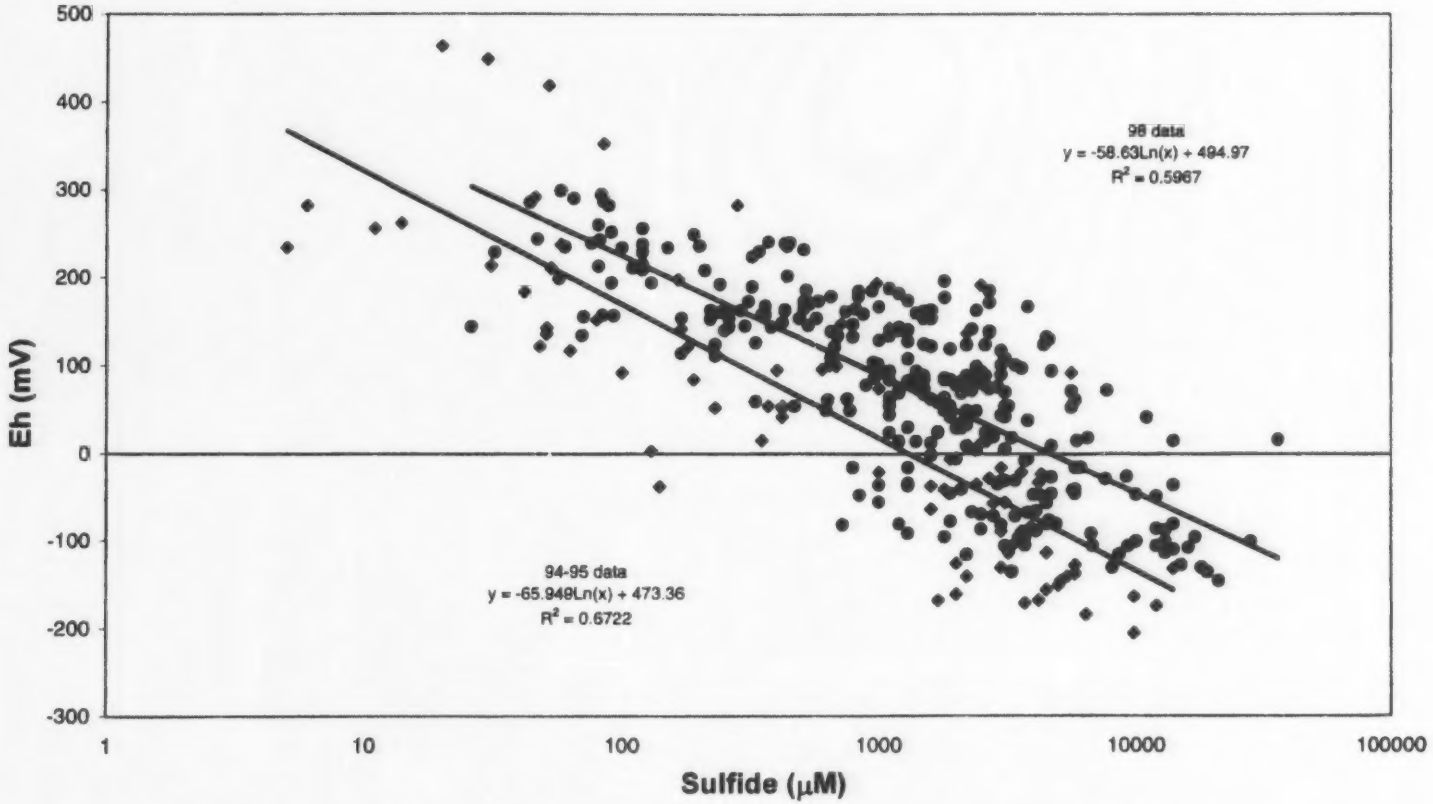

Fig. 1. Comparison of surface sediment geochemical research data in 1994-95 (◆) of Hargrave et al. (1995, 1997) and monitoring data in 1998 (●) from Appendix 1 as a semi-logarithmic plot.

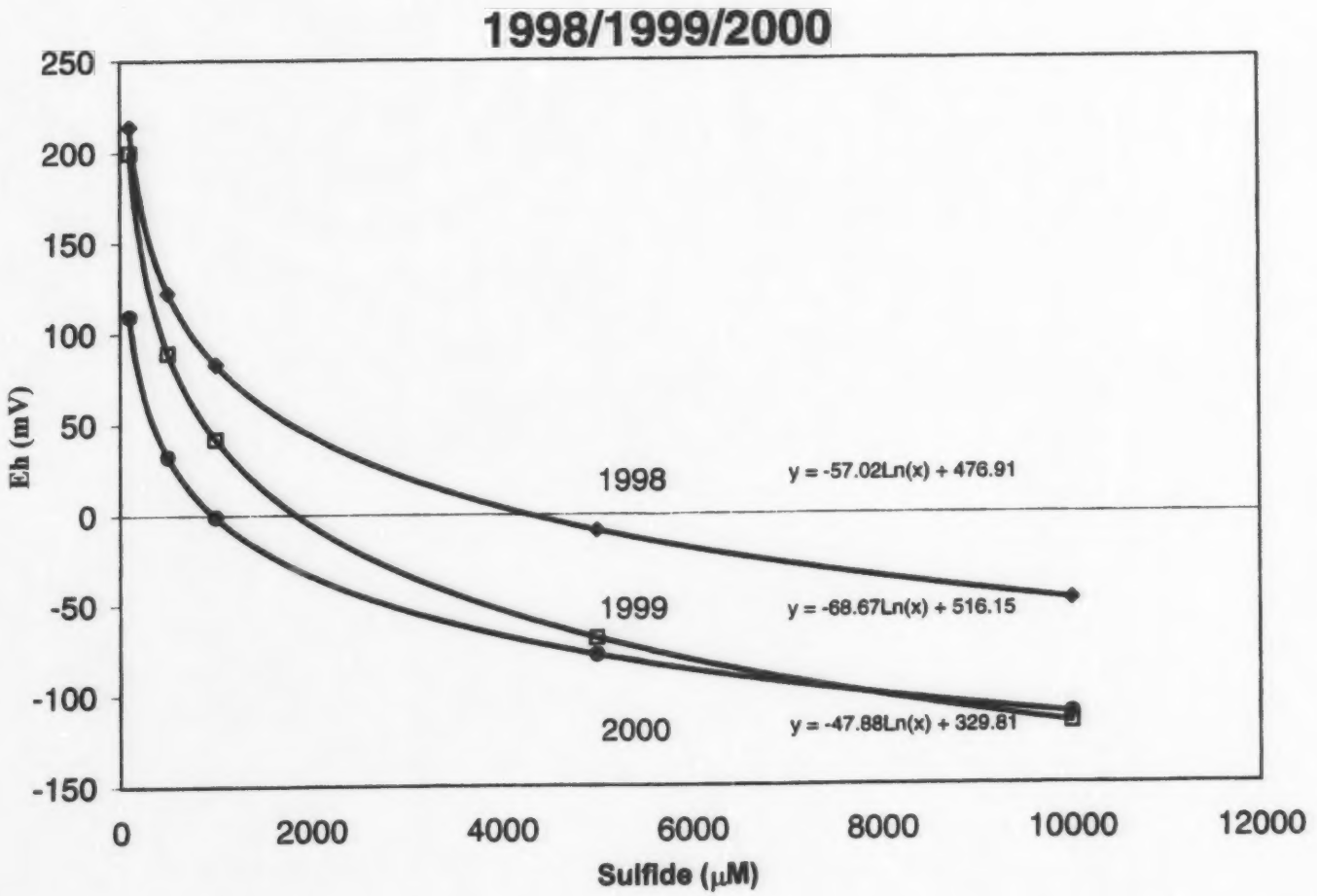

Fig. 2. Comparison of surface sediment geochemical monitoring data shown in Appendices 1-3 for 1998 (◆), 1999 (□) and 2000 (●) on arithmetic coordinates..

Appendix 1. Geochemical data taken from surface sediments under cage sites in the Bay of Fundy salmon mariculture industry for 1998.

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
1		620	b+	B+	A
		570	b+		
		1100	b+		
2	14	14000	b+	B+	A
	41	11000	b+		
	16	36000	b+		
	53	5600	b+		
	71	5600	b+		
	61	5800	b+		
3	138	1100	a	B+	C
	172	2700	b+		
	163	1600	b+		
	15	5900	b+		
	18	6500	b+		
	72	7700	b+		
	-106	3700	b-		
	-101	13000	c		
	-92	6700	b-		
4	139	2700	b+	B-	B
	70	3100	b+		
	108	3100	b+		
	-77	4600	b-		
	-68	3800	b-		
	-47	4000	b-		
5	64	1800	b+	B+	B
	78	2600	b+		
	74	2300	b+		
	-31	3400	b-		
	-46	4700	b-		
	-35	2900	b-		
6	18	3300	b+	B+	B
	5	3100	b+		
	24	2600	b+		
7	29		b+	B+	B
	36		b+		
	84		b+		
8	-27	4700	b-	B+	B
	-16	6100	b-		
	-42	5700	b-		
	34	2100	b+		
	42	1900	b+		
	90	3000	b+		
9	188	1100	a	A	A
	142	2300	a		
	134	1100	a		
	101	3400	a		
	89	2200	b+		
	76	2900	b+		
10	84	1800	b+	A	B
	78	2000	b+		
	62	1600	b+		
	154	1500	a		
	141	1300	a		
	144	1200	a		
11	83	1300	b+	B+	A
	72	1200	b+		
	94	1400	b+		
	104	950	a		
	78	890	b+		
	86	960	b+		
12	74	1200	b+	B+	A
	82	2100	b+		
	49	2200	b+		
13	-86	12000	b-	B-	B
	-81	14000	b-		
	74	2700	b+		
14	140	1200	a	A	A
	128	1300	a		
	134	690	a		
15	-97	3700	b-	B-	C
	-82	3000	b-		
	-106	6800	c		
	-96	17000	b-		
	-108	16000	c		
	-88	13000	b-		
16	162	740	a	A	A
	167	1000	a		
	174	1300	a		
	69	2100	b+		
	64	1100	b+		
	84	1100	b+		
17	60	5800	b+	B+	B
	54	4500	b+		
	69	1200	b+		
	-46	1100	b-		
	-57	1100	b-		
	-31	3100	b-		
18	30	1300	b+	B-	C
	44	1100	b+		
	62	1100	b+		
	-81	4500	b-		
	-97	3500	b-		
	-72	2800	b-		
	-87	2500	b-		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
	-92	1300	b-		
	-72	3400	b-		
19	68	4600	b+	A	A
	74	4400	b+		
	196	3000	a		
	130	2100	a		
	124	1800	a		
	117	1500	a		
20	-114	13000	c	B-	C
	-101	28000	c		
	-106	9300	c		
	54	3200	b+		
	42	3100	b+		
	25	1700	b+		
21	101	3000	a	A	A
	99	2400	b+		
	178	1800	a		
	167	3800	a		
	163	2400	a		
	185	2700	a		
22	-110	14000	c	C	C
	-116	8600	c		
	-106	3100	b-		
	-146	21000	c		
	-136	19000	c		
	-131	18000	c		
23	72	2300	b+	B+	B
	74	2200	b+		
	49	1800	b+		
	94	1100	b+		
	102	990	a		
	119	1900	a		
	44	3000	b+		
	29	2000	b+		
	124	2600	a		
	54	3100	b+		
	19	2800	b+		
	49	2400	b+		
	14	1400	b+		
	-6	2000	b-		
	24	1700	b+		
24					
25	179	830	a	A	A
	173	510	a		
	171	540	a		
26	186	830	a	A	A
	185	940	a		
	202	440	a		
27	93	1100	b+	A	A
	182	1200	a		
	174	520	a		
	192	240	a		
	190	320	a		
	174	580	a		
28	-81	4900	b-	B-	C
	-89	4100	b-		
	-116	2200	c		
	58	1700	b+		
	54	1900	b+		
	12	1600	b+		
	-66	4100	b-		
	-96	1800	b-		
	-81	1200	b-		
29	162	1500	a	A	A
	159	870	a		
	165	810	a		
	154	1600	a		
	160	1400	a		
	164	430	a		
30	89	1500	b+	B+	B
	84	1500	b+		
	84	1400	b+		
31	134	70	a	A	A
	199	57	a		
	194	91	a		
	209	120	a		
	211	110	a		
	194	130	a		
32	-101	10000	c	C	C
	-106	12000	c		
	-78	1900	b-		
	-136	3300	c		
	-131	8100	c		
	-128	15000	c		
33	155	71	a	A	A
	157	93	a		
	147	790	a		
	163	290	a		
	161	260	a		
	158	360	a		
	145	300	a		
	144	260	a		
	144	380	a		
34	-6	3800	b-	B-	B
	-16	5800	b-		
	9	4700	b+		
	94	2500	b+		
	74	1500	b+		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
	108	1300	a		
	-86		b-		
	-96		b-		
	-126		c		
35	144	26	a	A	A
	124	230	a		
	154	170	a		
	146	530	a		
	122	670	a		
	109	650	a		
36	215	120	a	A	A
	213	81	a		
	208	210	a		
	154	260	a		
	163	220	a		
	153	220	a		
37	179	650	a	A	A
	186	520	a		
	140	250	a		
	173	310	a		
	168	360	a		
	158	350	a		
38	239	76	a	A	A
	244	47	a		
	229	32	a		
	241	370	a		
	240	450	a		
	234	100	a		
39	249	190	a	A	A
	229	120	a		
	236	200	a		
	235	60	a		
	238	120	a		
	260	81	a		
40	154	1100	b+	B+	B
	154	2100	b+		
	149	1200	b+		
	94	330	b+		
	92	470	b+		
	74	770	b+		
	59	420	a		
	54	570	a		
	49	490	a		
	29		b+		
	24		b+		
	14		b+		
41	286	44	a	A	A
	282	89	a		
	299	58	a		
	290	65	a		
	295	83	a		
	287	85	a		
42	236	440	a	A	A
	230	340	a		
	234	150	a		
43	114	170	a	A	A
	126	330	a		
	111	230	a		
	157	84	a		
	161	240	a		
	165	510	a		
44	86	1800	b+	A	A
	84	1100	b+		
	96	1000	b+		
	252	91	a		
	243	82	a		
	256	120	a		
45	84	2600	b+	A	A
	84	2400	b+		
	89	1900	b+		
	224	510	a		
	232	430	a		
	239	320	a		
46	9	2200	b+	B+	B
	4	2400	b+		
	14	2600	b+		
	-48	840	b+		
	-56	1000	b+		
	-16	1300	b+		
	-37	1300	b+		
	-36	1300	b+		
	-16	790	b+		
47	61	630	b+	B+	B
	62	750	b+		
	49	620	b+		
	-36	1000	b+		
	-34	1300	b+		
	139	650	b+		
48	-46	1900	b-	B-	B
	-41	2100	b-		
	-47	4200	b-		
	-8	3700	b-		
	-2	1600	b-		
	-32	3000	b-		
49	-70	2500	b-	B-	C
	-67	2300	b-		
	-82	720	b+		
50	122	1600	a	A	B

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
	124	2200	a		
	138	2700	a		
	129	1000	a		
	133	790	a		
	125	1500	a		
51	-47	12000	b-	B+	B
	-49	10000	b-		
	-41	5800	b-		
	97	4700	b+		
	94	4500	b+		
	133	3600	a		
52	-26	14000	b-	B+	B
	-36	9200	b-		
	-29	7600	b-		
	33	3800	b+		
	42	2200	b+		
	38	2200	b+		
53	88	6300	b+	B+	B
	64	8200	b+		
	53	5800	b+		
	32	11000	b+		
	34	8400	b+		
	30	7700	b+		
54	-118	6900	c	C	C
	-126	13000	c		
	-122	12000	c		
	-91	10000	b-		
	-131	23000	c		
	-136	29000	c		
55	80	6100	b+	B+	B
	88	6200	b+		
	86	4100	b+		
	197	3100	a		
	103	7300	a		
	93	6700	b+		
56	-74	19000	b-	C	C
	-120	16000	c		
	-113	20000	c		
	-117	18000	c		
	-122	8800	c		
	-121	17000	c		
57	147	3800	a	A	B
	108	4300	a		
	123	5600	a		
58	39	1100	b+	B-	B
	-13	1300	b-		
	-4	2100	b-		
	143	750	a		
	-90	2200	b-		
	-77	2100	b-		
59	98	1100	b+	B-	B
	-26	3200	b-		
	3	2100	b+		
	-36	1700	b-		
	-56	1600	b-		
	-48	1500	b-		
60	-23	1600	b-	B-	B
	-21	2500	b-		
	-16	1800	b-		
	-72	1500	b-		
	-46	1800	b-		
	-49	1400	b-		
	-99	2500	b-		
	-76	1000	b+		
	-75	2400	b-		
	18	1200	b+		
	-4	1100	b-		
	-56	3500	b-		
	-26	4900	b-		
	-47	3900	b-		
	-6	3200	b-		
		3300	b+		
	-12	3200	b-		
62	-11	3300	b-	B+	B
	18	2000	b+		
	-2	1900	b-		
	9	1500	b+		
	4	1000	b+		
63	259	120	a	A	A
	229	130	a		
64	22	1300	b+	B+	B
	28	1400	b+		
	16	1400	b+		
	14	830	b+		
	38	1100	b+		
65	-58	1100	b+	B+	B
	-54	1000	b+		
	-27	1300	b+		
	-15	740	b+		
	-22	780	b+		
	-2	680	b+		

Appendix 2. Geochemical data taken from surface sediments under cage sites in the Bay of Fundy salmon mariculture industry for 1999.

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
54	-70	7200	b-	B-	C
	112	8000	c		
	-106	7000	b-		
	-96	8400	b-		
	-74	9200	b-		
	-102	9000	c		
49	-95	4200	b-	B-	B
	-106	6000	c		
	-90	2300	b-		
	-70	5100	b-		
	-82	6000	b-		
	-60	4500	b-		
62	-20	2100	b-	B-	B
	-18	1600	b-		
	-4	1000	b+		
	-40	2600	b-		
	-51	4300	b-		
	-16	1800	b-		
21	0	2600	b+	B-	B
	5	1400	b-		
	-16	2000	b-		
	-20	2200	b-		
	-10	2300	b-		
	-21	1200	b+		
25	215	180	a	A	A
	212	500	a		
	196	230	a		
26	203	350	a	A	A
	208	110	a		
	194	620	a		
	226	100	a		
	240	340	a		
	208	310	a		
27	60	670	b+	B+	A
	41	720	b+		
	52	110	a		
28	10	1100	b+	B+	B
	-5	900	b+		
	-12	1400	b-		
	27	800	b+		
	10	1200	b+		
	18	700	b+		
	90	2100	b+		
	62	1400	b+		
	80	1600	b+		
30	18	1000	b+	B+	B
	-3	700	b+		
	25	1400	b+		
	45	600	b+		
	30	200	b+		
	21	500	b+		
29	45	900	b+	B+	A
	52	840	b+		
	12	610	b+		
	40	720	b+		
	60	940	b+		
	31	610	b+		
53	-70	4200	b-	B-	B
	-41	2800	b-		
	-50	3100	b-		
	-20	2100	b-		
	5	1600	b+		
	-16	4000	b-		
14	12	800	b+	B+	A
	41	700	b+		
	20	1050	b+		
15	-90	9000	b-	B-	C
	-110	11200	c		
	-120	8300	c		
	-20	6400	b-		
	-71	8700	b-		
	-63	7100	b-		
19	80	900	b+	B+	A
	73	730	b+		
	52	620	b+		
	146	210	a		
	150	195	a		
	112	380	a		
40	174	290	a	B+	A
	161	310	a		
	180	200	a		
	64	1100	b+		
	51	600	b+		
	40	420	b+		
	17	960	b+		
	20	810	b+		
	46	500	b+		
38	218	59	a	A	A
	230	110	a		
	231	140	a		
	193	320	a		
	180	290	a		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
	206	210	a		
	196	145	a		
	190	180	a		
	201	290	a		
36	60	130	a	A	A
	81	200	a		
	106	89	a		
	27	310	b+		
	20	400	b+		
	25	305	b+		
34	-30	1800	b-	B-	B
	-41	2100	b-		
	10	3900	b+		
	-60	2700	b-		
	-64	2000	b-		
	-71	4100	b-		
	10	2400	b+		
	12	3000	b+		
	-5	2100	b-		
43	50	620	b+	B+	A
	42	700	b+		
	56	890	b+		
	85	310	b+		
	92	420	b+		
	110	290	a		
41	195	110	a	A	A
	210	140	a		
	180	210	a		
	196	90	a		
	200	240	a		
	180	160	a		
	30	240	a		
	41	390	b+		
	50	500	b+		
	80	290	a		
	87	340	b+		
	84	170	a		
45	60	1100	b+	A	A
	72	310	b+		
	68	720	b+		
	180	260	a		
	191	210	a		
	170	90	a		
44	210	720	a	A	A
	200	600	a		
	195	510	a		
	160	120	a		
	152	210	a		
	150	170	a		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
33	224	120	a	A	A
	210	160	a		
	216	110	a		
	216	410	a		
	230	260	a		
	200	200	a		
31	40	710	b-	A	A
	38	605	b+		
	36	410	b+		
	199	205	a		
	182	190	a		
	206	290	a		
	170	80	a		
	163	140	a		
	180	260	a		
39	160	150	a	A	A
	170	210	a		
	169	200	a		
	170	75	a		
	192	89	a		
	200	116	a		
32	-20	7200	b-	B-	C
	-41	4100	b-		
	-39	6000	b-		
	-40	5400	b-		
	-56	7200	b-		
	-61	3600	b-		
64	195	600	a	A	A
	210	520	a		
	186	290	a		
	188	140	a		
	196	105	a		
	214	74	a		
59	28	920	b+	B+	B
	40	1300	b+		
	56	1000	b+		
	129	460	a		
	141	510	a		
	160	720	a		
56	-10	1700	b-	B-	C
	-30	2300	b-		
	-22	5600	b-		
	-6	3100	b-		
	-12	2000	b-		
	10	1100	b+		
61	-202	12000	c	C	C
	-210	9000	c		
	-196	10500	c		
	-220	7800	c		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
	-200	9400	c		
	-234	11000	c		
58	-15	1100	b-	B-	B
	-32	9200	b-		
	-36	1350	b-		
	-40	790	b+		
	-40	1820	b-		
	-42	2110	b-		
55	12	460	b+	B+	B
	17	810	b+		
	25	1130	b+		

Appendix 3. Geochemical data taken from surface sediments under cage sites in the Bay of Fundy salmon mariculture industry for 2000.

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
33	239	85	a	A	A
	230	60	a		
	231	140	a		
	250	0	a		
	248	40	a		
	251	30	a		
12	160	0	a	A	A
	165	40	a		
	161	10	a		
26	-38	3600	b-	B+	A
	18	1210	b+		
	21	680	b+		
	88	210	a		
	72	106	a		
	48	45	a		
11	95	610	b+	A	A
	86	750	b+		
	90	980	b+		
	241	0	a		
	238	55	a		
	238	40	a		
	172	290	a		
	170	360	a		
	160	375	a		
38	218	0	a	A	A
	236	0	a		
	230	20	a		
	206	65	a		
	202	10	a		
	198	105	a		
8	-6	1200	b+	B+	A
	15	930	b+		
	3	1160	b+		
	18	970	b+		
	-4	1410	b-		
	10	630	b+		
	36	710	b+		
	12	600	b+		
	16	505	b+		
9	40	540	b+	B+	A
	12	720	b+		
	16	310	b+		
	6	650	b+		
	-10	805	b+		
	18	490	b+		
	51	600	b+		
	36	710	b+		
	29	565	b+		
1	102	241	a	A	A
	96	390	b+		
	109	306	a		
27	53	120	a	A	A
	60	360	b+		
	36	210	b+		
19	21	640	b+	B-	A
	40	1060	b+		
	38	1310	b+		
	-61	2640	b-		
	-45	2600	b-		
	-52	1850	b-		
44	28	110	a	A	A
	17	196	a		
	15	220	a		
	50	0	a		
	61	60	a		
	43	0	a		
25	108	0	a		
	96	15	a		
	103	10	a		
42	4	960	b+	B+	A
	15	810	b+		
	18	750	b+		
	-36	1410	b-		
	6	1360	b+		
	10	2170	b+		
	21	570	b+		
	18	905	b+		
	36	1060	b+		
39	38	460	b+	B+	A
	26	790	b+		
	25	700	b+		
	4	920	b+		
	18	1060	b+		
	-6	1640	b-		
31	44	860	b+	A	A
	41	730	b+		
	20	1190	b+		
	156	45	a		
	141	180	a		
	130	310	a		
	148	275	a		
	146	105	a		
	139	160	a		
35	141	0	a	A	A

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
	138	0	a		
	136	40	a		
	42	25	a		
	50	165	a		
	44	205	a		
	162	65	a		
	170	0	a		
	164	15	a		
41	12	0	a	A	A
	36	0	a		
	6	45	a		
	41	35	a		
	50	0	a		
	36	10	a		
	-15	610	b+		
	-18	275	a		
	-18	540	b+		
	-6	590	b+		
	4	1460	b+		
	2	300	b+		
37	174	0	a	A	A
	180	115	a		
	161	140	a		
	104	15	a		
	110	40	a		
	95	105	a		
64	46	190	a	B+	A
	40	365	b+		
	42	284	a		
	16	450	b+		
	21	605	b+		
	41	710	b+		
32	-26	1260	b+	B+	B
	-10	980	b+		
	-6	900	b+		
	-6	1490	b-		
	-3	1100	b+		
	-5	1265	b+		
40	-92	3210	b-	B+	B
	-86	3000	b-		
	-90	2650	b-		
	4	610	b+		
	8	350	b+		
	10	390	b+		
	40	465	b+		
	38	910	b+		
	40	410	b+		
	154	460	a		
	150	610	a		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
	156	1100	a		
23	-96	2610	b-	B+	B
	-81	2300	b-		
	-84	1965	b-		
	-40	1420	b-		
	-37	1860	b-		
	-29	1190	b+		
	6	260	a		
	4	940	b+		
	12	800	b+		
	-34	985	b+		
	-30	1130	b+		
	-41	1410	b+		
	15	260	a		
	6	350	b+		
	4	565	b+		
3	84	900	b+	B-	B
	62	1100	b+		
	31	750	b+		
	-68	1100	b+		
	-32	1200	b+		
	-51	1340	b-		
	-88	2300	b-		
	-92	1850	b-		
	-75	2160	b-		
2	-8	810	b+	B+	B
	53	760	b+		
	71	506	b+		
	106	510	a		
	132	430	a		
	96	605	b+		
18	-13	1200	b+	B+	B
	-22	950	b+		
	16	1000	b+		
	6	1460	b+		
	-18	1300	b-		
	-56	1850	b-		
	-36	2600	b-		
	-18	3400	b-		
	-43	2100	b-		
	-8	890	b+		
	12	1210	b+		
	-10	720	b+		
63	-35	1460	b-	B+	B
	-82	1900	b-		
	-41	1060	b+		
	51	610	b+		
	17	500	b+		
	46	340	b+		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
56	168	1260	a	B-	B
	146	1110	a		
	106	1630	a		
	-4	820	b+		
	26	600	b+		
	18	1410	b+		
	42	2650	b+		
	16	1910	b+		
	-8	2300	b-		
60	16	740	b+	B-	B
	31	1100	b+		
	6	920	b+		
	-96	1860	b-		
	-72	2100	b-		
	-41	1400	b-		
	-100	1160	b+		
	-93	1200	b+		
	-90	1190	b+		
	-124	6200	c		
	-112	5000	b-		
	-86	2960	b-		
10	-98	960	b+	B+	B
	-82	1410	b-		
	-87	1260	b+		
	-103	1040	b+		
	-95	1360	b-		
	-90	1100	b+		
16	-6	1080	b+	B+	B
	15	650	b+		
	-19	840	b+		
	-151	4560	b-		
	-72	1280	b+		
	-36	2360	b-		
22	-82	5460	b-	B+	B
	-64	7210	b-		
	-71	1040	b+		
	-10	1240	b+		
	8	690	b+		
	21	1030	b+		
13	-41	2960	b-	B-	B
	-50	3020	b-		
	-49	3410	b-		
28	-66	4040	b-	B-	B
	-42	3910	b-		
	-51	2860	b-		
	-118	7100	c		
	-72	5320	b-		
	-63	5600	b-		
4	-72	3620	b-	B-	B
	-65	3110	b-		
	-69	2060	b-		
	-17	970	b+		
	-12	1230	b+		
	-18	810	b+		
62	-10	2620	b-	B-	B
	-36	1890	b-		
	-18	2016	b-		
	15	1150	b+		
	-6	930	b+		
	-4	1070	b+		
43	-22	610	b+	B-	B
	-10	1940	b-		
	-18	1505	b-		
	-111	2960	b-		
	-114	7140	c		
	-106	4130	b-		
	178	0	a		
	185	0	a		
	163	175	a		
51	-25	2620	b-	B-	B
	-30	3610	b-		
	-29	2820	b-		
	-57	4305	b-		
	-60	5440	b-		
	-58	5260	b-		
34	31	495	b+	B+	B
	36	280	a		
	145	360	a		
	161	410	a		
	95	695	b+		
	18	1430	b+		
	6	1110	b+		
	-5	1360	b-		
53	-76	1495	b-	B-	B
	-71	2130	b-		
	-75	6560	b-		
	-42	1610	b-		
	-35	1140	b+		
	-40	2070	b-		
5	-54	2160	b-	B-	B
	-30	2050	b-		
	-36	4100	b-		
	-112	6230	c		
	-96	6960	b-		
	-106	7820	c		
47	-88	5260	b-	B-	B
	-102	6810	c		
	-96	7650	b-		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
	-30	2130	b-		
	-26	4610	b-		
	-36	2310	b-		
52	-16	1210	b+	B-	B
	-10	3460	b-		
	-13	1190	b+		
	62	1610	b+		
	58	540	b+		
	51	1705	b+		
	-112	3610	b-		
	-108	5430	b-		
	-110	7160	c		
55	5	1510	b+	B+	B
	-10	1460	b-		
	-12	2910	b-		
	-3	960	b+		
	-8	1120	b+		
	-2	840	b+		
20	-106	6200	c	C	C
	-112	7320	c		
	-96	8610	b-		
	-145	9600	c		
	-131	11100	c		
	-150	7340	c		
	-73	3160	b-		
	-69	2210	b-		
	-80	2360	b-		
46	-51	1460	b-	B-	C
	-64	2810	b-		
	-70	2240	b-		
	-116	6410	c		
	-120	8600	c		
	-118	3140	b-		

Farm number	Redox mV_{NHE}	Sulfide µM	Geo (1)	Geo (2)	EMP
54	-116	6800	c	C	C
	-95	7200	b-		
	-87	12450	b-		
	-110	8300	c		
	-131	7950	c		
	-106	9060	c		
48	-62	6200	b-	C	C
	-106	8310	c		
	-43	8630	b-		
	-142	14500	c		
	-160	12500	c		
	-110	8630	c		
61	-110	6720	c	B-	C
	-106	9610	c		
	-95	2430	b-		
	-98	4850	b-		
	-118	5135	b-		
	-124	6060	c		
15	-126	3690	b-	B-	C
	-110	4510	b-		
	-118	6090	c		
	-145	5610	b-		
	-140	8820	c		
	-141	10865	c		
58	-114	5400	b-	B-	C
	-106	6200	c		
	-121	2910	b-		
	-117	7650	c		
	-96	7920	b-		
	-125	4165	b-		